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Charm mixing and CPV.

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The LHCb detector is a dedicated heavy flavour experiment operating at the Large Hadron Collider at CERN. During 2010 and 2011 LHCb collected some of the world's largest samples of charm hadron decays, which have been used to search for Charge-Parity (*CP*) violation in the charm sector. Highlights of these searches, including the first observation of *CP* violation in the decays of charm hadrons are presented.

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1. Introduction

The LHCb detector [1] at the Large Hadron Collider (LHC) is a single arm spectrometer optimized for the study of charm and beauty hadrons. The LHCb acceptance covers the pseudo-rapidity range $2 < \eta < 5$; in what follows "transverse" means transverse to the LHC beamline. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system has a momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV$/c$ to 0.6% at 100 GeV$/c$, an impact parameter[1] resolution of 20 μm for tracks with high transverse momentum, and a decay time resolution of 50 fs. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and pre-shower detectors, an electromagnetic calorimeter, and a hadronic calorimeter. Muons are identified by a muon system composed of alternating layers of iron and multiwire proportional chambers.

The interest in studying *CP*-violation (*CPV*) in the charm sector stems from the fact that it is predicted to be small in the Standard Model. The argument, summarized in [2], is that charm hadrons decay into quarks of the first two generations whose mixing matrix is real, and hence there is no *CPV* possible in the dominant tree-level decays. *CPV* can manifest itself through penguin or box diagrams, but since these are suppressed by $V_{cb}V_{ub}^{*}$ the allowed level of Standard Model *CPV* does not exceed 1%, and indeed effects greater than 1% have been ruled out by previous experiments [3]. This makes it important to improve the precision of charm *CPV* measurements to below the 0.1% level, in order to constrain the precise nature of *CPV* in charm. In addition, although D^0 mixing is well established by now, no single experiment has achieved 5 σ precision yet, and improving the precision on the mixing parameters will aid the interpretation of any time-dependent *CPV* which may be observed.

LHCb is ideally poised to carry out such a programme because of the LHC's large open charm cross-section of 6.10 ± 0.93 mb [4]: one in every ten LHC interactions results in the production of a charm hadron. This amounts to approximately 1.5 MHz of produced events which contain a charm hadron, of which only about 1 - 2 kHz can be written to storage for offline analysis. For this reason LHCb deploys a number of efficient real-time selection algorithms, called triggers, to select the most interesting charm events for later analysis. As a result, LHCb collects e.g. around 5×10^3 tagged $D^{*\pm} \to \left(D^0 \to K^+K^-\right)\pi^\pm$, or around 3×10^5 untagged $D^0 \to K^-\pi^+$, decays per pb^{-1} of integrated luminosity; at the time of writing, it already has the world's largest samples of two and three body $D^\pm_{(s)}, D^0$ decays on tape.

Three different measurements are presented here : a measurement of time-integrated *CPV* in two body D^0 decays, measurements of time-dependent *CPV* and mixing in two body D^0 decays, and a search for time-integrated *CPV* in three-body decays of $D^\pm$ mesons.

[1] Impact parameter is the transverse distance of closest approach between a track and a vertex, most commonly the primary proton-proton interaction vertex.

2. Time-integrated *CP* asymmetries in D^0 decays

The LHCb measurement of time-integrated *CP* asymmetries in two-body D^0 meson decays using data collected during 2011 running is described in detail in [5]. Time integrated asymmetries are measured for both untagged

$$A_{\text{raw}}(f) = \frac{N\left(D^0 \to f\right) - N\left(\bar{D}^0 \to f\right)}{N\left(D^0 \to f\right) + N\left(\bar{D}^0 \to f\right)}, \tag{2.1}$$

and tagged

$$A_{\text{raw}}(f)^* = \frac{N\left(D^{*+} \to D^0(f)\pi_s^+\right) - N\left(D^{*-} \to \bar{D}^0(f)\pi_s^-\right)}{N\left(D^{*+} \to D^0(f)\pi_s^+\right) + N\left(D^{*-} \to \bar{D}^0(f)\pi_s^-\right)}, \tag{2.2}$$

D^0 decays into the final state f, where the charge of the $\pi_s^\pm$ tags the produced flavour of the D^0. In the case of decays into self-conjugate final states (K^+K^-, $\pi^+\pi^-$) only tagged asymmetries can be measured. The measured asymmetries are labeled "raw" as they are made up of not only the *CP* asymmetries, but also of various production and detection asymmetries caused by the initial matter-antimatter asymmetry present in LHC collisions and the nature of the LHCb detector. In particular, the efficiency of the RICH particle identification varies with the track charge and transverse momentum. In order to cancel these nuisance asymmetries, the difference of raw asymmetries in the KK and $\pi\pi$ modes is defined

$$\Delta A_{CP} = A_{\text{raw}}\left(K^+K^-\right)^* - A_{\text{raw}}\left(\pi^+\pi^-\right)^*. \tag{2.3}$$

This difference in raw asymmetries is equal to the difference in the physics asymmetries to first order, in the limit that the detection and production asymmetries cancel exactly between the modes. It is obtained by measuring the number of signal events in each tagged decay mode; example fits to the mass spectra are shown in Fig. 1. Although the first order cancellation is sufficient for the current level of statistical precision, subtle effects in certain regions of D^* or $\pi_s^\pm$ momentum transverse to the LHC beamline (p_T) and pseudorapidity (η) must be considered. In particular, there are regions of the LHCb detector acceptance where only one of the $D^{*\pm}$ charges can be reconstructed because the LHCb magnet sweeps the tagging pions of opposite charge out of the acceptance.

Instead of relying on an average cancellation, fits are performed in twelve (p_T,η) bins and a weighted average used to arrive at the final value of ΔA_{CP}. Additional robustness checks are performed by varying the particle identification criteria, using an alternative signal selection, and monitoring the result stability as a function of time, as shown in Fig. 2. The final result obtained with a dataset corresponding to approximately 0.6 fb^{-1} of integrated luminosity is

$$\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%, \tag{2.4}$$

where the first uncertainty is statistical and the second systematic, dominated by the modelling of the signal lineshape. This measurement represents the first evidence of *CPV* in the decays of charm hadrons.

PoS(HQL 2012)033

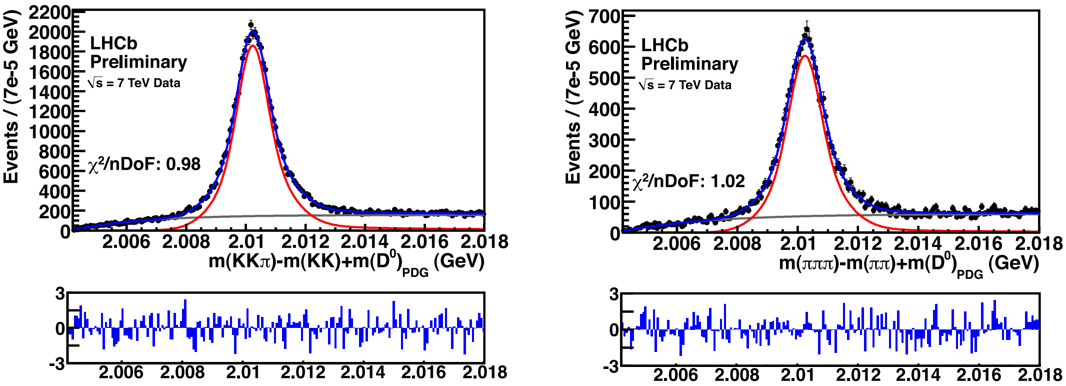

Figure 1: Fits to the difference between the D^* and D^0 masses for a subset of the data, where the D^0 decays into K^+K^- (left) and $\pi^+\pi^-$ (right).

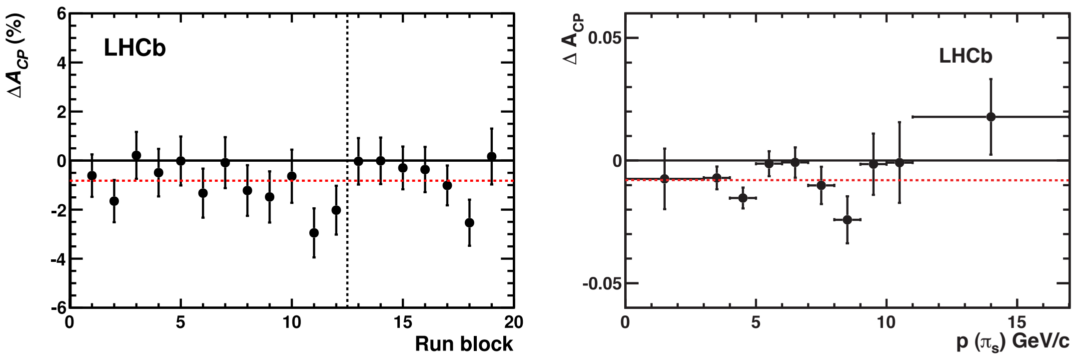

Figure 2: Stability of ΔA_{CP} as a function of run number (left) and slow pion transverse momentum (right).

3. Mixing and time-dependent *CP* asymmetries in D^0 decays

Like neutral B mesons, neutral charm D^0 mesons can mix, leading to mass and width differences between the eigenstates $\Delta m_D \equiv m_2 - m_1$ and $\Delta\Gamma_D \equiv \Gamma_2 - \Gamma_1$. The mixing parameters are defined as $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/(2\Gamma)$.

The measurement of time-dependent *CP* asymmetry in the decays of D^0 mesons into a *CP* eigenstate can be related to the measurement of the lifetimes of the D^0 and $\bar{D}^0$ mesons in decays to this eigenstate, A_Γ:

$$A_\Gamma = \frac{\hat{\Gamma}\left(D^0 \to K^+K^-\right) - \hat{\Gamma}\left(\bar{D}^0 \to K^+K^-\right)}{\hat{\Gamma}\left(D^0 \to K^+K^-\right) + \hat{\Gamma}\left(\bar{D}^0 \to K^+K^-\right)} \approx \frac{(A_m + A_d)}{2} y\cos(\phi) - x\sin(\phi), \quad (3.1)$$

where ϕ is the *CP*-violating weak phase, and $A_m \approx 1 - |\frac{q}{p}|^2$, where q,p are the amplitudes which define the mass eigenstates in terms of the flavour eignestates. The parameter $A_d \approx 1 - |\frac{\bar{A}_f}{A_f}|^2$ describes the relative magnitude of the decay amplitudes $A_f, \bar{A_f}$, while $\hat{\Gamma}$ are the measured inverse lifetimes of D^0 decays to *CP* eigenstates.

In addition, the parameter y_{CP} can be defined as [6]

$$y_{CP} = \frac{\hat{\Gamma} + \hat{\bar{\Gamma}}}{2\Gamma} - 1 \approx \eta_{CP}\left[\left(1 - \frac{A_m^2}{8}\right) y\cos\phi - \frac{A_m}{2} x\sin\phi\right],$$

where Γ is the measured inverse lifetime of D^0 decays to the Cabibbo-favoured flavour eigenstate $K\pi$. In the limit of CP conservation y_{CP} equals the mixing parameter y.

Because of the LHC's prodigious production of charm, LHCb is forced to deploy lifetime-biasing selections already at the trigger level, in order to maximize signal yield for a given output bandwidth. The analysis then pivots on the ability to measure the D^0 decay-time acceptance of this selection in a data-driven manner. This is done by measuring the decay-time acceptance on an event-by-event basis: for every event, the primary interaction from which the D^0 originated is moved along the direction of the D^0 momentum, thus varying the D^0 decay-time. At each point the full event selection chain, including the software trigger, is reevaluated, and the event accepted or rejected. This builds up the decay-time acceptance for that event, which is a sum of top-hat functions (since at each step the event either passes or fails). For more details of this procedure see [7, 8, 9].

An additional complication is the production of so-called "secondary" charm, where the D^0 originates from a B meson decay. Although twenty times less abundant than "prompt" charm produced directly in the pp interaction, secondary charm has greater momentum and displacement from the pp interaction and hence passes the trigger much more efficiently. If ignored it can lead to a significant upward bias in the measured lifetimes. The impact parameter of the D^0 with respect to the pp interaction is a good discriminant between prompt and secondary charm, and is used to fit for the fractions of signal events of each kind, as shown in Fig. 3.

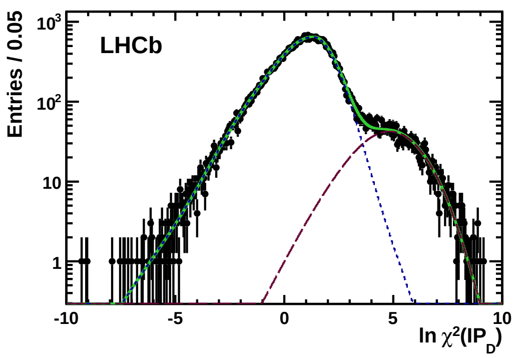

Figure 3: Prompt and secondary charm signals as a function of the D^0 impact parameter χ^2. Short-dashed blue is prompt, long dashed magenta is secondary, and the total fit is represented by a solid green line.

Having taken into account the decay-time acceptance and secondary contribution, the lifetimes Γ, $\hat{\Gamma}$, and $\hat{\bar{\Gamma}}$ are measured using an unbinned maximum likelihood fit, as shown in Fig. 4. The results obtained with a dataset corresponding to approximately 28 pb^{-1} of integrated luminosity are [10].

$$A_\Gamma = (-5.9 \pm 5.9 \pm 2.1) \times 10^{-3}, \tag{3.2}$$

$$y_{CP} = (5.5 \pm 6.3 \pm 4.1) \times 10^{-3}. \tag{3.3}$$

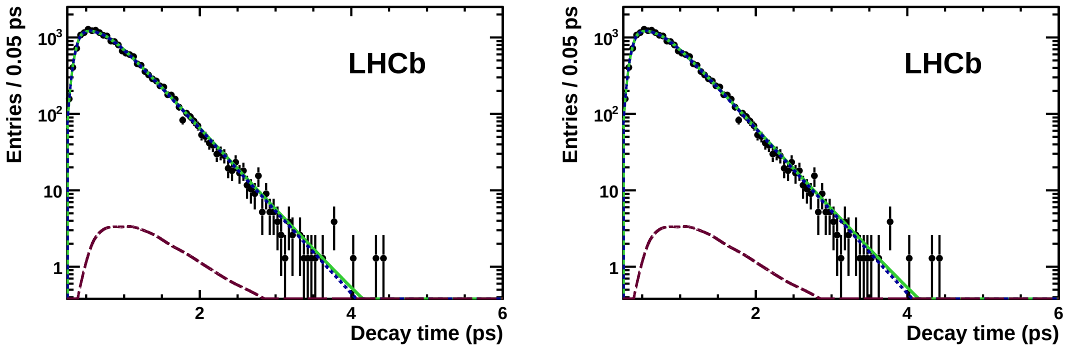

Figure 4: Fits to the $D^0 \to K^+K^-$ (left) and $\bar{D}^0 \to K^+K^-$ (right) lifetime.

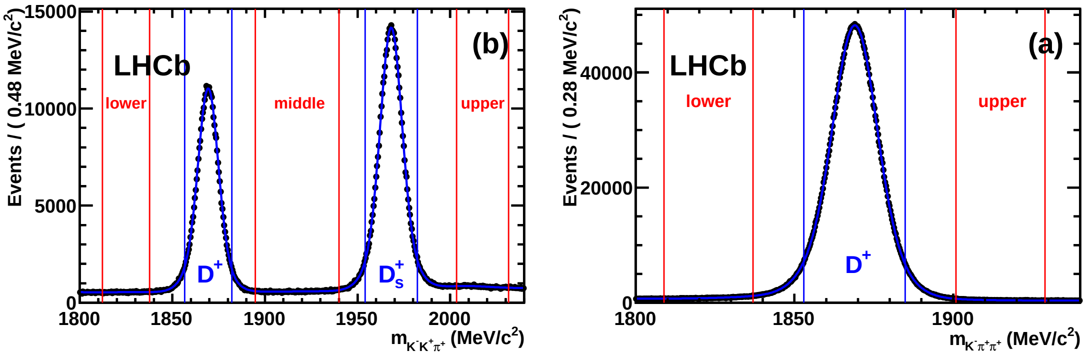

Figure 5: Mass distributions of the $D^{\pm}_{(s)} \to K^+K^-\pi^{\pm}$ (left), and $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ (right) candidates. The signal regions are indicated by vertical blue lines around the Gaussian peaks, while sideband regions are indicated by vertical red lines.

4. Time-integrated *CP* asymmetries in $D^{\pm}$ decay

The Cabbibo-suppressed three body decay $D^{\pm} \to K^+K^-\pi^{\pm}$ is studied in order to search for *CPV* effects in the Dalitz plot distribution of the KK and $K\pi$ masses. In order to remain sensitive to large local asymmetries even in those cases where the *CPV* is negligible when integrated across the Dalitz plane, the following metric is defined

$$S^i_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) - \alpha^2 N^i(D^-)}}, \tag{4.1}$$

where the parameter α describes any overall asymmetries, including detection and production effects

$$\alpha = \frac{N_{tot}(D^+)}{N_{tot}(D^-)}. \tag{4.2}$$

The metric S^i is measured in individual bins of the Dalitz plot, and the overall distribution of the measured S^i values is compared to the distribution expected in the case of zero *CPV*, namely a Gaussian of unit width and mean zero.

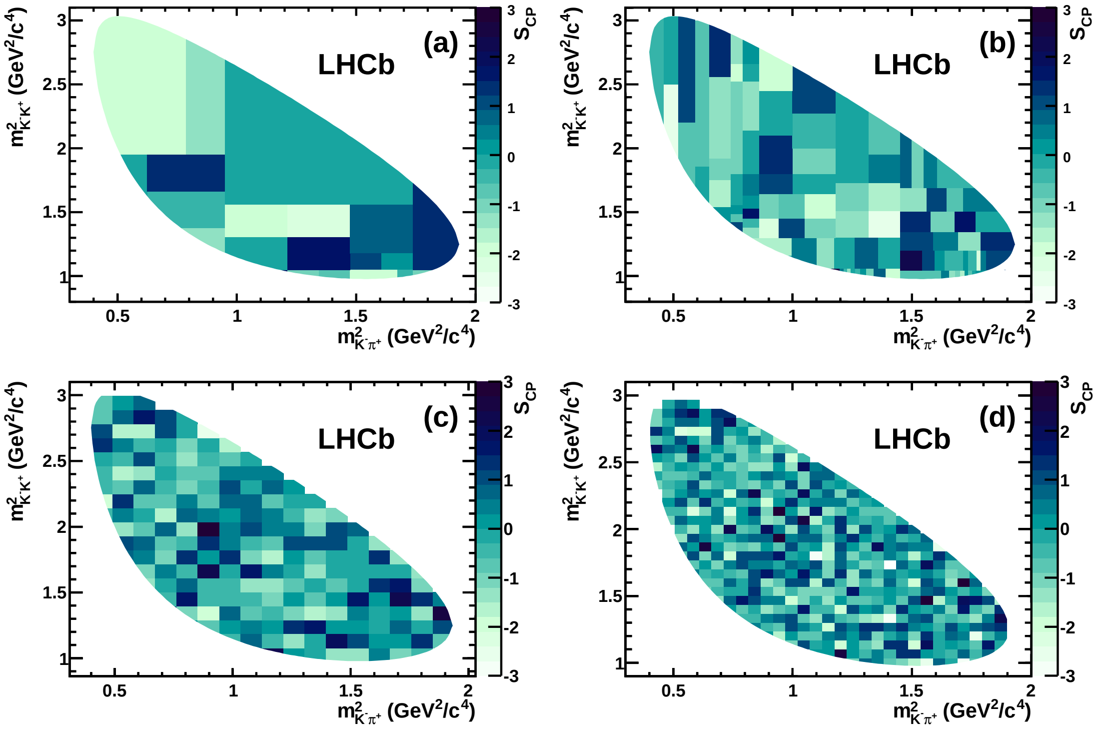

Figure 6: S^i_{CP} distributions for the decay mode $D^\pm \to K^+K^-\pi^\pm$ in the Adaptive I (top left), Adaptive II (top right), Uniform I (bottom left), and Uniform II (bottom right) binnings.

This method is known as the Miranda procedure and is described in more detail in [11]. Its sensitivity to *CPV* effects has been validated in extensive studies of simulated events. The LHCb analysis was performed with a dataset corresponding to approximately 37 pb^{-1} of integrated luminosity, and used the closely related Cabbibo-favoured decay modes $D^\pm \to K^\mp\pi^\pm\pi^\pm$ and $D_s^\pm \to K^+K^-\pi^\pm$ as controls. The signals used in the analysis are shown in Fig. 5. Four different binnings are investigated, and the distributions of the S^i_{CP} values for the signal mode $D^\pm \to K^+K^-\pi^\pm$ are shown in Fig. 6 for each binning. The results are consistent with no *CPV*, with p-values for consistency with no *CPV* varying between around 10% and around 80%.

5. Conclusion

This contribution has reviewed measurements of time-integrated and time-dependent *CP* asymmetries in the decays of D^0 and D^+ mesons performed with the LHCb detector at the LHC. The large open charm production cross-section of the LHC affords LHCb an unprecedented statistical reach in these decays, while the precise tracking and particle identification systems enable LHCb to reconstruct the signals with high purity. This statistical reach lead LHCb to make the first observation of *CPV* in the charm sector, as described in this contribution. At the time of writing, LHCb has collected more than 1.5 fb^{-1} of data, and is pursuing not only updates of the analyses presented here but also measurements of *CPV* and mixing in many related charm hadron decays in order to precisely understand the nature of *CPV* in the charm sector.

References

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PoS(HQL 2012)033